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Use of Coreless Inductances in the Operation of Synchronous Machines

Electrical Engineering

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USE OF CORELESS INDUCTANCES
IN THE
OPERATION OF SYNCHRONOUS MACHINES

BY

LLOYD GARRISON
GEORGE ANNIS WILLIAMS

THESIS

FOR

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

PRESENTED JUNE, 1907

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May 28, 1907

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

Morgan Brooks.

HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING

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THE USE OF CORELESS INDUCTANCES IN THE OPERATION OF SYNCHRONOUS MACHINES

In the past the operation of synchronizing and paralleling large alternators has been attended with great risk. As this is one of the routine duties in power plant operation, investigators have made an exhaustive study of its principles with the idea of reducing its dangers. Various arrangements and schemes have been devised, but among the most recent and probably the most promising, is that introduced by Professor Morgan Brooks and Mr.M.K.Akers of the University of Illinois. This device consists simply of an inductance placed between the machine to be synchronized and the bus bars. The inductance not only serves to choke down the current flowing between the alternators but also has an elastic action which tends to pull the machines together. It is necessary of course that the action be instantaneous. For this reason no iron can be used in the inductance as it has been found by experiment that the iron does not become magnetized the instant the switch is closed but, instead, the magnetism lags behind and allows considerable momentary current to flow.

Since no iron could be used in the inductance it became desirable to obtain data for the design of coils to be used in paralleling alternators and it was to present such data that this thesis was prepared.

The method followed was to build inductance coils of various dimensions, measure their resistance, and compare the observed

inductance with that computed for the coilsby various formulas. With this end in view two sets of coils were constructed. One set, a cross-section of which is shown in Fig.1, consisted of ten coils each of about ten cm. mean radius and two cm. axial length. Each coil was wound with 100 turns of No. 19 double cotton covered wire. The other set, shown in Fig.2, consisted of a set of flat or pancake coils about two and five tenths cm. axial length. The mean radii of the different coils in this set varied from eleven to twenty eight cm. In construction the set was equivalent to one large coil of 2300 turns with terminals brought out every 100 turns.

The impedance method was used throughout in determining the inductance of the coils. Standard instruments were used to measure the current and fall of potential. Three readings were taken for each determination of the inductance which was computed by the formula,

$$L = \frac{1}{2\pi f}\frac{}{I}\sqrt{E^2 - (IR)^2}$$

The mean of the three determinations of L was taken as the real value.

The observed inductance was compared with the computed inductance figured by the theoretical formula, one given by Parshall and Hobart (Prof. Perry's) in their work on dynamo design, and an approximate formula given by R.P.Jackson in his discussion of "Lightning Protective Apparatus" in the December 1906, issue of the Proceedings of the A.I.E.E.

The theoretical formula for coils without iron is derived as follows;

The field inside the coil is $4\pi nI$ per unit of area, in which n is the number of turns per unit of length and I, the current flowing. The total flux is therefore $4\pi rnI$. Since this flux passes through nl turns of wire the self inductance is

$$L = 4\pi^2 r^2 n^2 l + 10^9$$

or if N is the total number of turns,

$$L = 4\pi^2 r^2 N^2 + 10^9 l$$

This formula should hold for all shapes of coils, but it has been found by experiment that the formula holds fairly well for coils in which the length is at least ten times the diameter. For coils of small length as compared with their diameter, the inductance, as computed by this formula should be large, but practically its value is small. It was because of this variation that it was necessary to obtain other formulas and test their accuracy by experiment. The reasons why the formula does not hold for flat coils has not yet been fully explained, but magnetic leakage, or end effect, has been held responsible for a large part of the discrepancy.

The formula given by Prof. Perry, which is of a more or less empirical nature, is as follows;

$$L = \frac{N^2 r^2}{(0.0184r + 0.031\ l + 0.035\ w)\ 10^9}$$

Mr. R. P. Jackson's rule is only an approximation and is quite simple. The rule as given is ; The inductance in henries equals

the length of a mean turn in inches multiplied by the square of the number of turns, and divided by 10^8.

$$L = 2\pi r N^2 \div 10^8$$

Or with r expressed in cm.

$$L = 7.9 \pi r N^2 \div 10^9$$

The first tests were made on the set of long coils in which the total length was about equal to the diameter. Plate I gives the curve obtained, using length as abscissae and inductance as ordinates, by placing the ten coils in series and then reducing the length by cutting out the end coils. The percent variation of the observed from the theoretical inductance was very large for short coils, but as the length increased the observed inductance seemed to fall into a straight line parallel to the theoretical curve. The percent variation is thus a decreasing function of the length.

Another test was made on the long coil to determine the variation in inductance of the end coils on account of the end effect. Plate II shows the results obtained. A current was passed through the series of coils and simultaneous readings were taken for the middle and each of the other coils. The readings for the middle coil were kept constant in this test in order to secure uniform data. The inductance of the separate coils was found to decrease uniformly as taps were made from the center towards the ends. Referred to the center coil, the decrease in inductance of the end coils was 36.1 %.

A series of tests was next made on the set of pancake coils. Plate III compares the results obtained from observation and by

computation from the theoretical formula for tests made upon the coils in series. The first reading was taken with all the coils in series, the succeeding readings were taken by cutting out the inner coils one at a time. Plate V gives similar curves plotted for the coils taken separately. It is readily seen from these curves that for coils of relative dimensions as given above, the theoretical formula is worse than useless.

Plate IV shows curves obtained from observed data for the coils in series, and from data computed by Jackson's and Perry's formulas. Plate VI gives curves obtained in the same way for each coil taken separately. Jackson's formula is intended as a very rough approximation and as such holds fairly well for coils having a ratio 1:d not greater than .4 nor less than .1, and the ratio of inner radius to outer radius between the limits 1 and .5. Prof. Perry's formula is, however, very accurate when applied to coils of the shape for which it is intended. This formula is given as applicable to coils having small length and cross-section of winding as compared with their diameter. Experiment showed, however, that it is quite accurate for the same differences of radii as given for Jackson's formula. For the coils having greatest diameters there was practically an exact agreement between computed and observed data. From Plate IV there does not seem to be much difference between the two formulas, each agreeing quite closely with the observed data for differences of radii not too large. The accuracy of Perry's formula is shown very conclusively on Plate VI, however, by the coincidence, within the limits of error, of the curve derived from this formula with the observed results.

In order to determine the most economically shaped coil the curve on Plate VII was plotted by means of the data and curves obtained in these tests. This curve shows the variation in inductance of coils with equal weights of wire but of different shapes. The computations were based on 120 pounds of No.6 wire, and formulas were used which from the curves agreed best with the given relative dimensions. Perry's formula was used for coils up to a length equal to nearly half the diameter. For values not differing greatly from this ,Perry's, Jackson's , and the theoretical formula, agreed quite closely when the later was corrected by means of the curve on Plate I.

The curve shows a maximum value of the inductance for ratios 1:d varying from .1 to .5 . For the case under consideration, using 120 pounds of No. 6 wire, the maximum inductance occurred with a value 1:d of about .3 . Above the value .5 for 1:d the inductance decreases very rapidly. The reason for this is easily seen from the theoretical formula in which the numerator is the square of the constant length of wire and the denominator, 10 1, an increasing function. For small values of 1:d to which Perry's formula applies the same reason is evident. In Perry's formula the numerator is constant and the denominator, an increasing function. This, of course, causes the curve to drop off for very low values of 1:d.

CONCLUSIONS

It seems from the foregoing results that Perry's formula satisfies the conditions necessary to the design of coreless inductances for use in synchronizing alternators. Such coils to have a maximum inductance should be quite large in diameter as compared with the length and cross-section of winding. As far as could be determined by this investigation Perry's formula gave results which agreed very closely with those obtained by experiments upon coils of that nature.Any formula is liable to considerable difference from observed conditions when it depends upon measurements of coils in which the ratio of one measurement to another is small, but under the given conditions, which were made as nearly as possible like those that would obtain in practice, Perry's formula was a great deal more accurate than any other used.

Geo. A. Williams

Lloyd Garrison

KEY TO SYMBOLS AND ABBREVIATIONS

I = Current

E = Fall of Potential

R = Resistance

f = Frequency

L = Inductance

l = Length of Coil

w = Width of Winding of Coil

r = Mean Radius of Coil

CROSS SECTION OF COIL

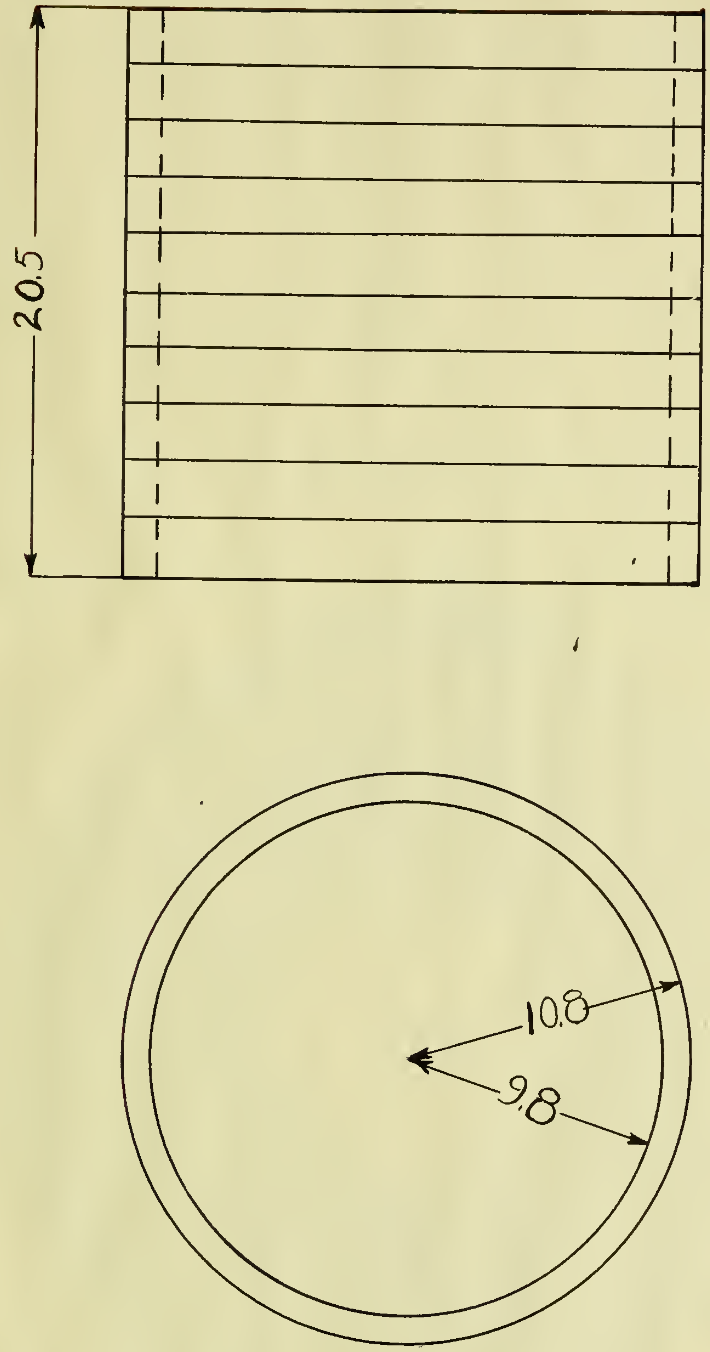

Fig. 1
Long Coil

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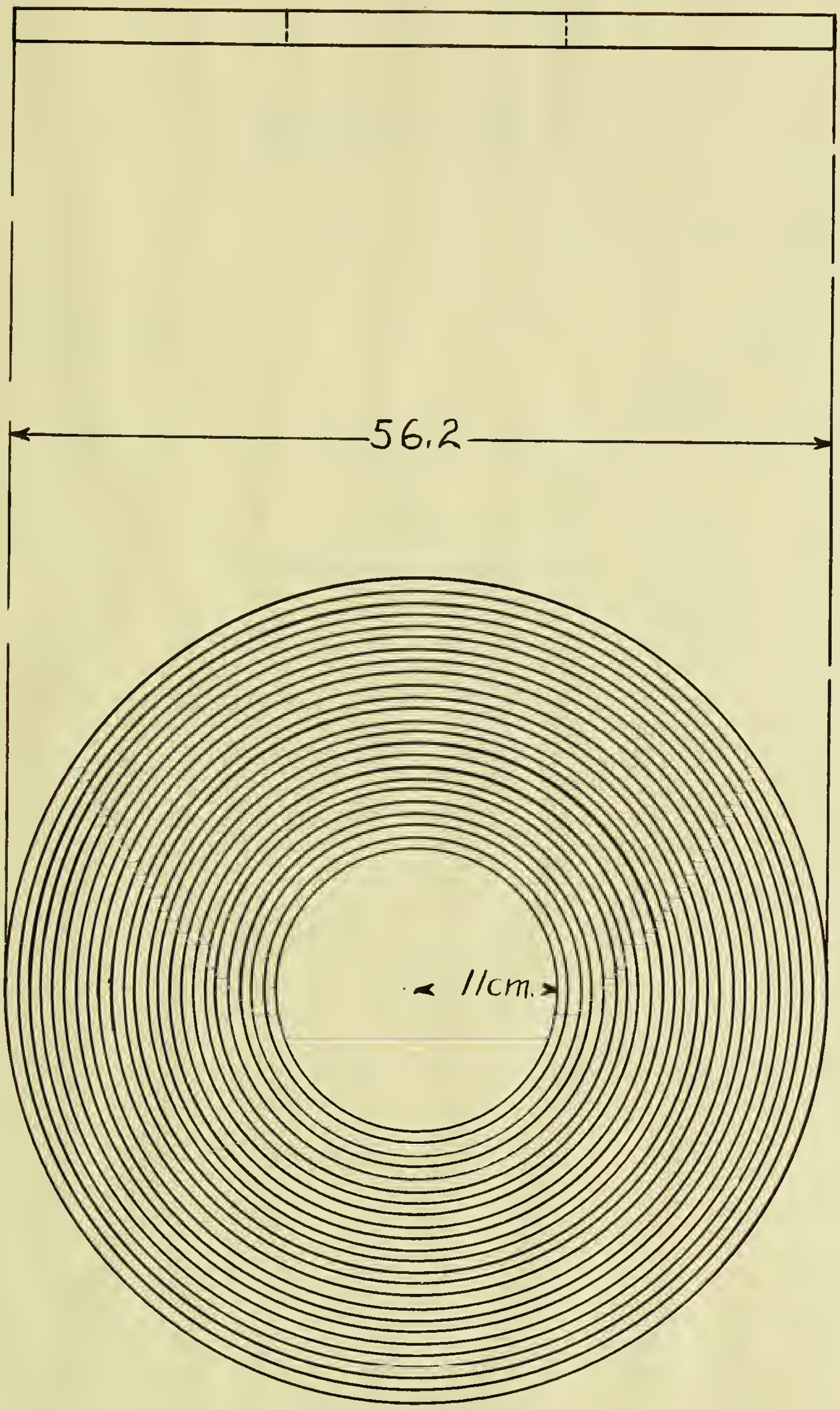


Fig. 2
Flat Coil

DATA SHEET PLATE I.

OBSERVED					COMPUTED	
					Jackson	Theoretical
Coils	l	N	r	L	L	L
1 - 10	21.0	1000	10.3	.1370	.253	.198
1 - 9	18.9	900	"	.1160	.205	.178
1 - 8	16.8	800	"	.0950	.162	.158
1 - 7	14.7	700	"	.0701	.124	.138
1 - 6	12.6	600	"	.0581	.091	.119
1 - 5	10.5	500	"	.0456	.063	.099
1 - 4	8.4	400	"	.0335	.041	.079
1 - 3	6.3	300	"	.0219	.023	.059
1 - 2	4.2	200	"	.0110	.010	.040
1	2.1	100	"	.0035	.003	.021

DATA SHEET PLATE II

Observed

Coils	l	r	N	L
1	2.1	10.3	100	.0099
2	4.2	"	"	.0119
3	6.3	"	"	.0132
4	8.4	"	"	.0134
5	10.5	"	"	.0137
6	12.6	"	"	.0137
7	14.7	"	"	.0134
8	16.8	"	"	.0129
9	17.9	"	"	.0120
10	21.0	"	"	.0099

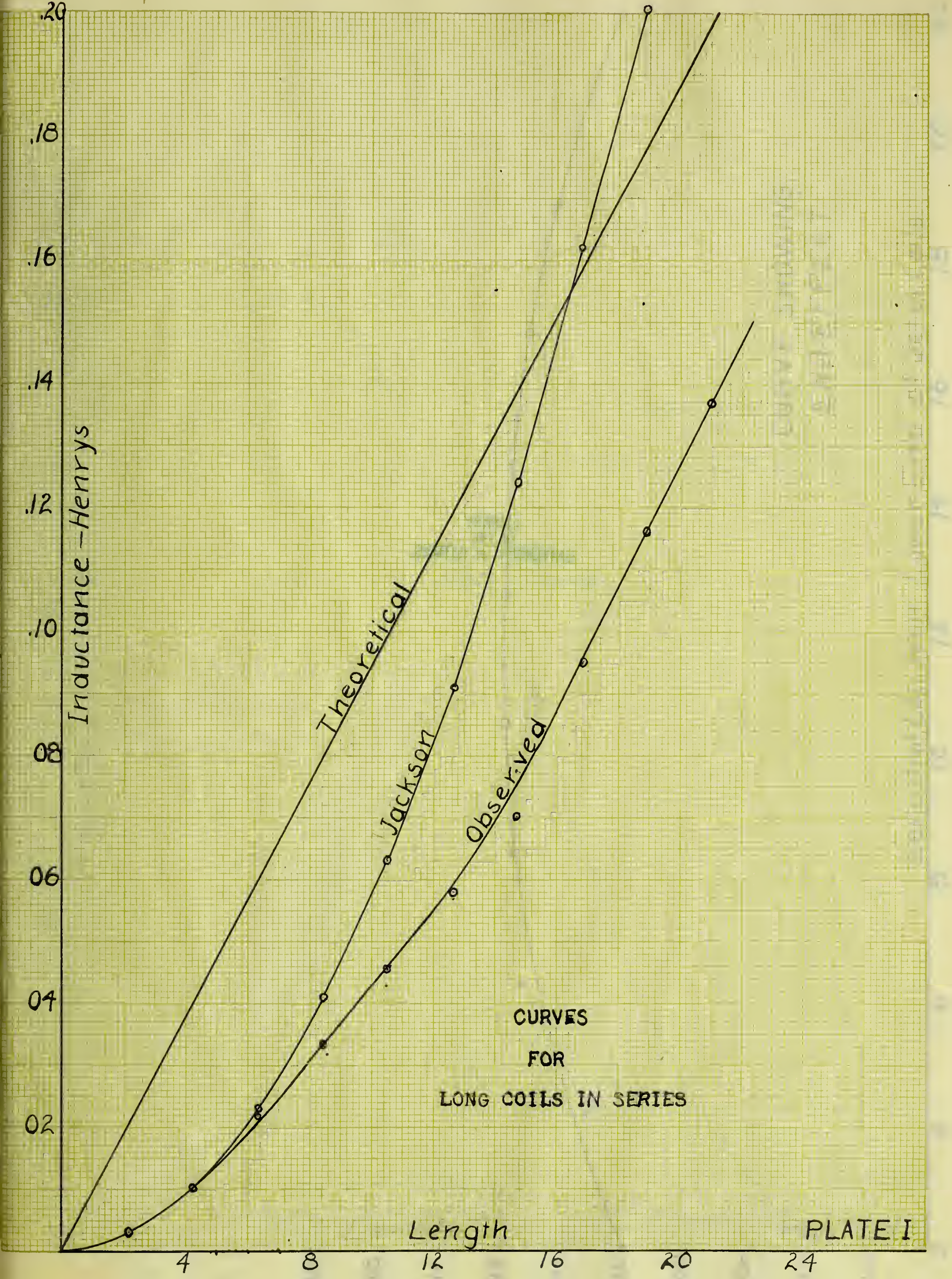
DATA SHEET PLATES III AND IV.

		OBSERVED				COMPUTED		
						Jackson	Theoretical	Perry
Coils	l	N	r	L	w	L	L	L
1 - 23	2.55	2300	19.0	1.56	17.9	2.48	29.7	1.81
2 - 23	"	2200	20.0	1.51				
3 - 23	"	2100	20.6	1.46	16.3	2.25	29.1	1.82
4 - 23	"	2000	21.1	1.41				
5 - 23	"	1900	21.5	1.37	14.8	1.92	25.9	1.64
6 - 23	"	1800	22.0	1.30				
7 - 23	"	1700	22.3	1.25	13.2	1.59	22.3	1.50
8 - 23	"	1600	22.7	1.18				
9 - 23	"	1500	23.0	1.11	11.7	1.28	18.5	1.31
10 - 23	"	1400	23.4	1.03				
11 - 23	"	1300	23.8	1.03	10.1	.99	14.8	1.10
12 - 23	"	1200	24.2	.88				
13 - 23	"	1100	24.6	.79	8.6	.74	11.4	.88
14 - 23	"	1000	24.9	.70				
15 - 23	"	900	25.2	.61	7.0	.51	8.0	.66
16 - 23	"	800	25.6	.52				
17 - 23	"	700	26.0	.43	5.5	.32	5.1	.44
18 - 23	"	600	26.3	.33				
19 - 23	"	500	26.7	.24	3.9	.17	2.8	.25
20 - 23	"	400	27.1	.17				
21 - 23	"	300	27.4	.10	2.3	.06	1.0	.10
22 - 23	"	200	27.7	.04				
23	"	100	28.1	.013	.78	.01	.12	.013

DATA SHEET PLATES V.AND VI.

OBSERVED						COMPUTED		
						Jackson	Theoretical	Perry
Coils	1	N	r	L	w	L	L	L
1	2.55	100	11.0	.00312	.78	.00272	.0188	.00392
2	"	"	12.0	.00451	"			
3	"	"	13.1	.00509	"	.00324	.0226	.00495
4	"	"	14.0	.00482	"			
5	"	"	14.8	.00542	"	.00366	.0340	.00580
6	"	"	15.3	.00547	"			
7	"	"	16.5	.00595	"	.00408	.0422	.00663
8	"	"	17.2	.00647	"			
9	"	"	17.8	.00713	"	.00443	.0494	.00730
10	"	"	18.6	.00750	"			
11	"	"	19.5	.00795	"	.00482	.0590	.00817
12	"	"	20.2	.00826	"			
13	"	"	21.1	.00865	"	.00522	.0690	.00902
14	"	"	21.7	.00900	"			
15	"	"	22.3	.00925	"	.00551	.0768	.00962
16	"	"	23.0	.01000	"			
17	"	"	23.8	.01040	"	.00590	.0877	.01040
18	"	"	24.5	.01050	"			
19	"	"	25.3	.01100	"	.00628	.0993	.01120
20	"	"	26.0	.01180	"			
21	"	"	26.6	.01220	"	.00658	.1102	.01190
22	"	"	27.3	.01270	"			
23	"	"	28.1	.01290	"	.00695	.1223	.01270

2 E



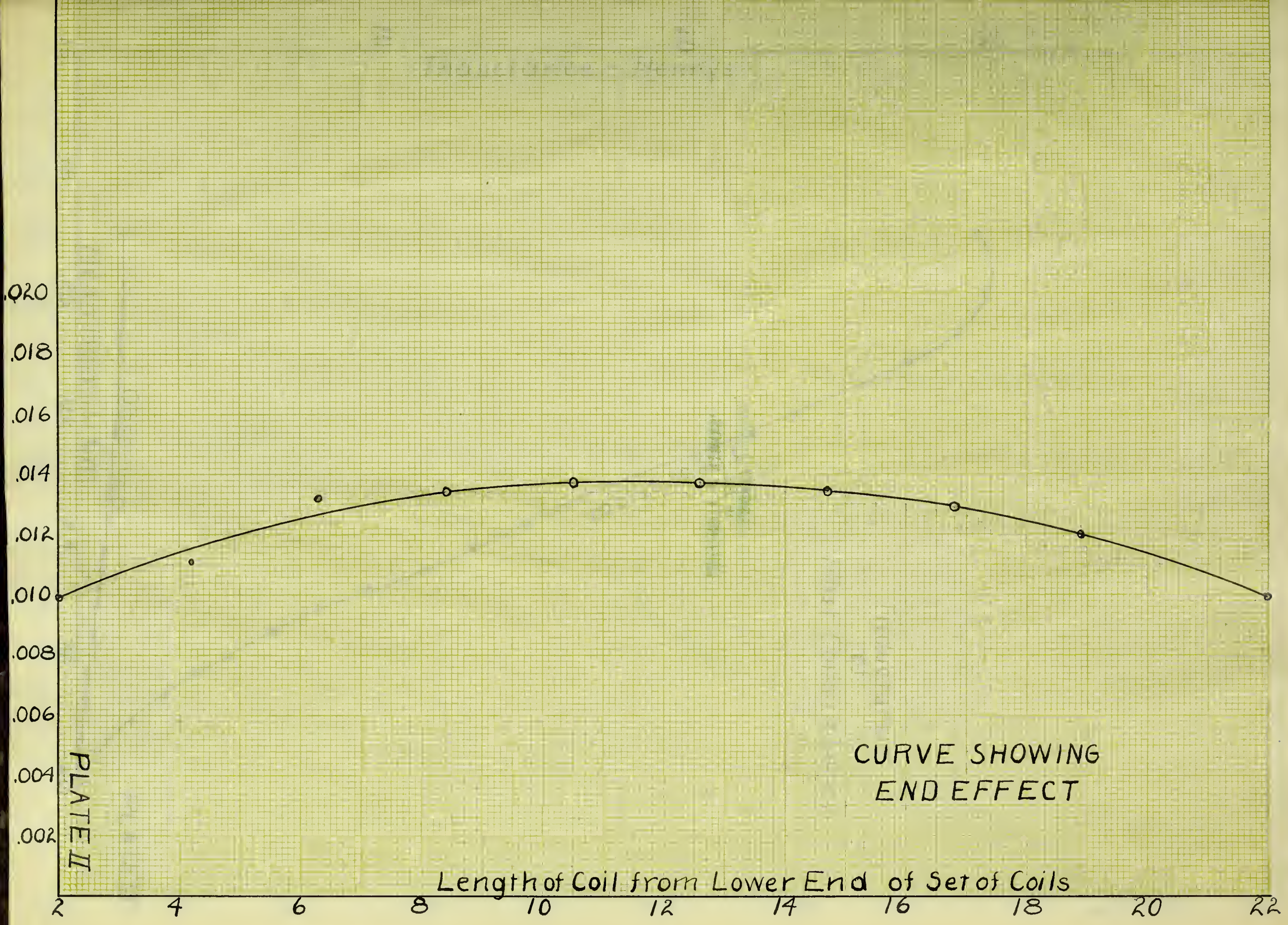
CURVES

FOR

LONG COILS IN SERIES

PLATE I

PLATE II



CURVE SHOWING
END EFFECT

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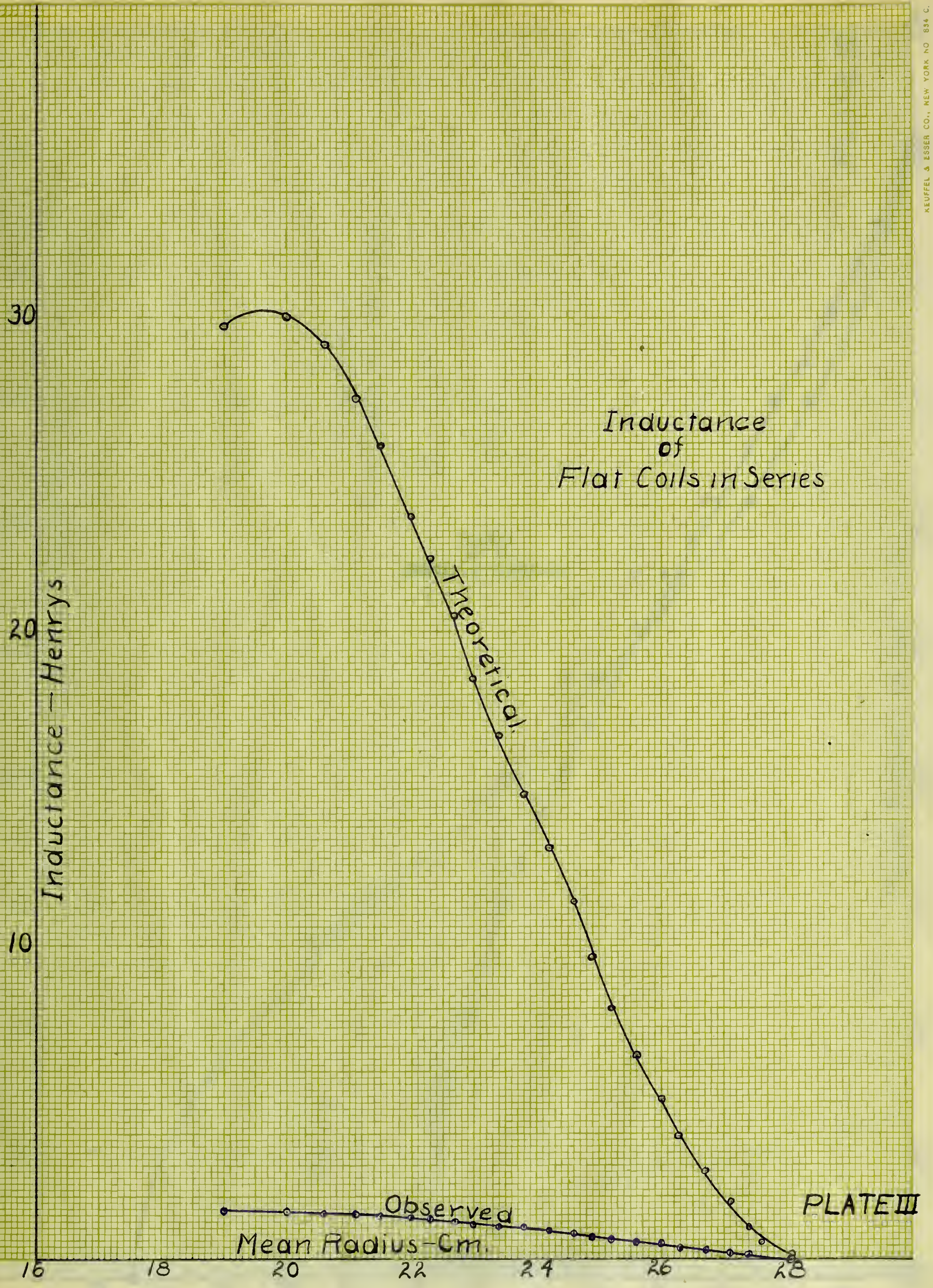

PLATE III

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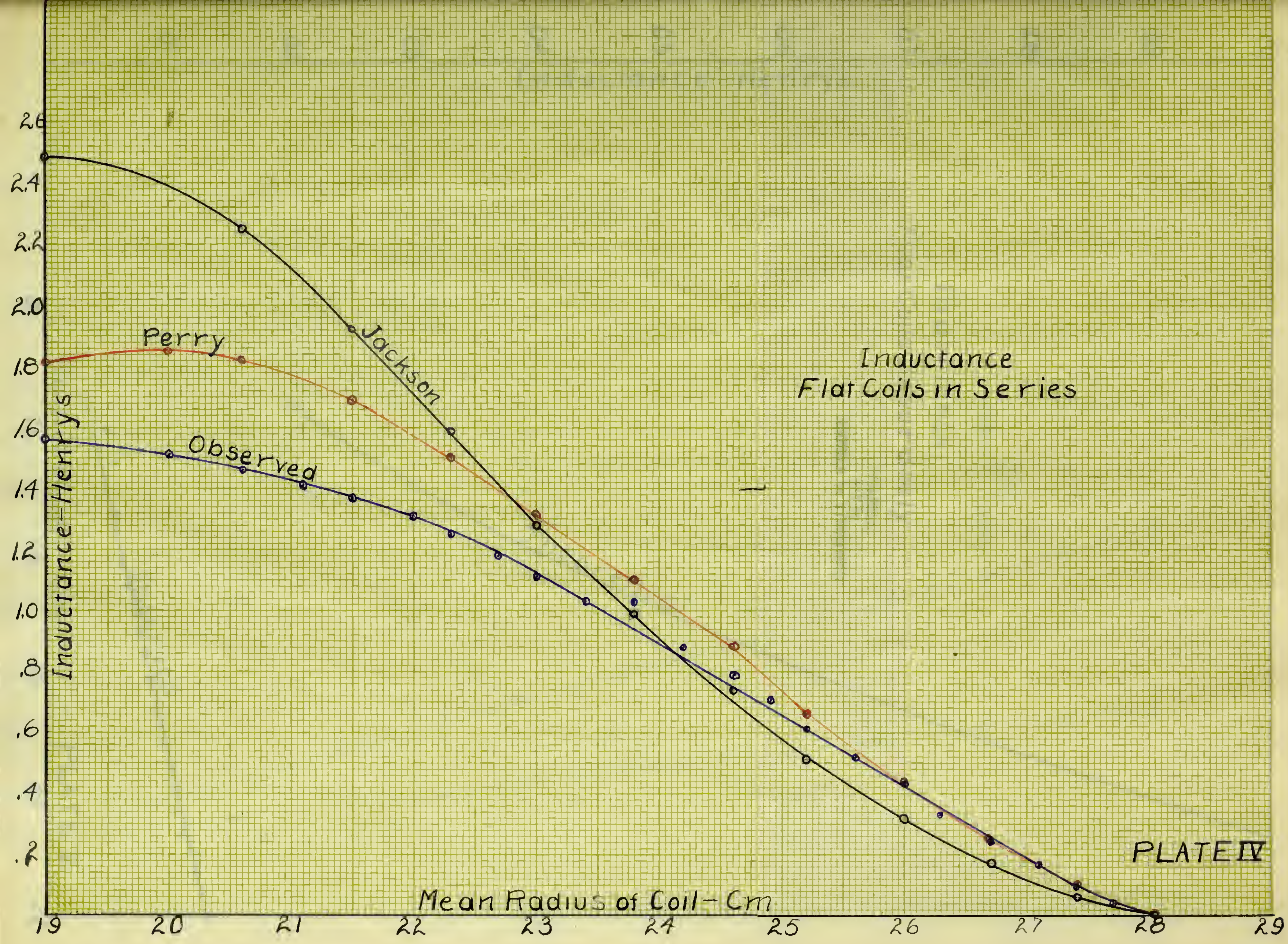
PLATE IV



Inductance
Flat Coils in Series

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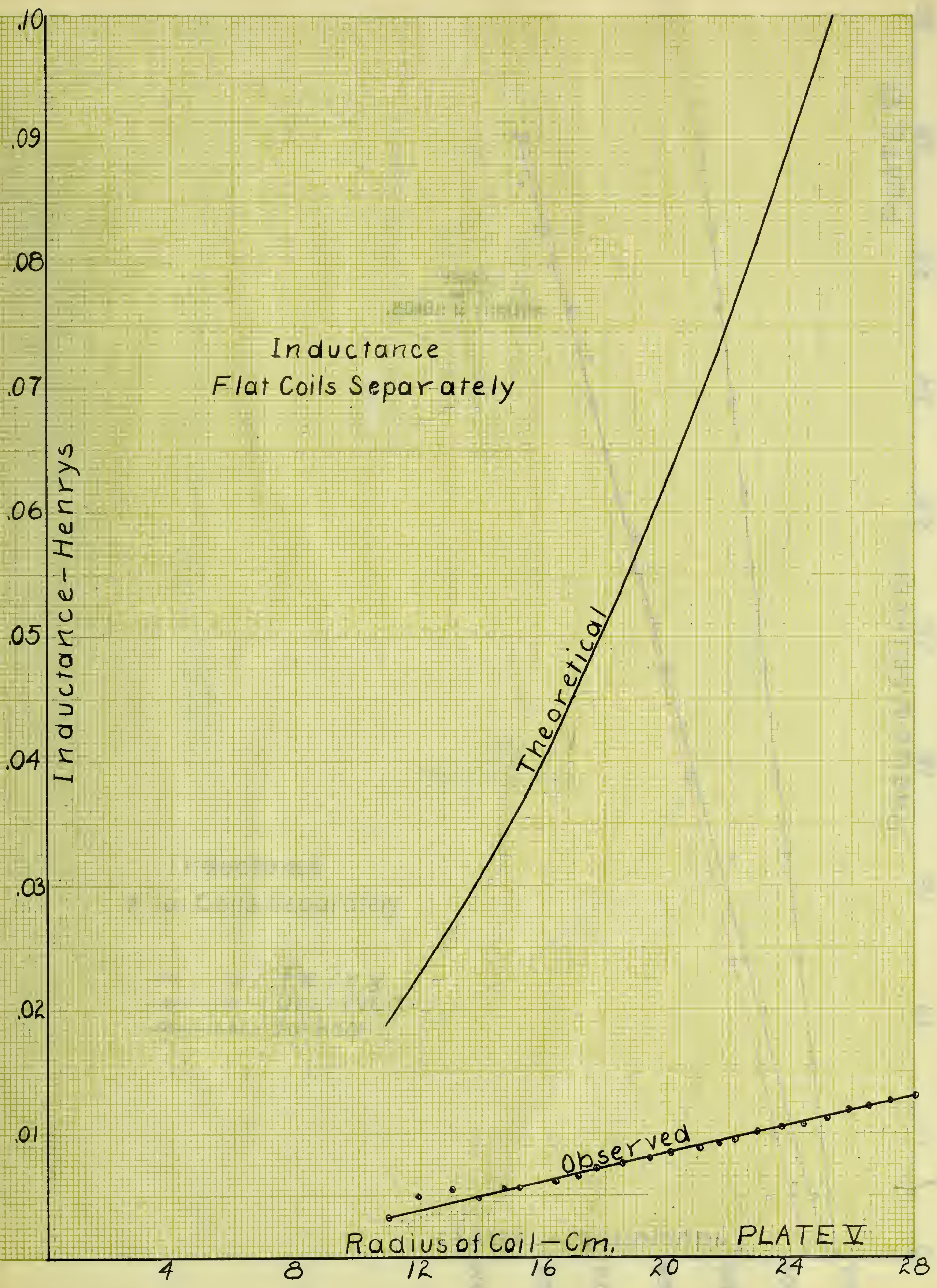
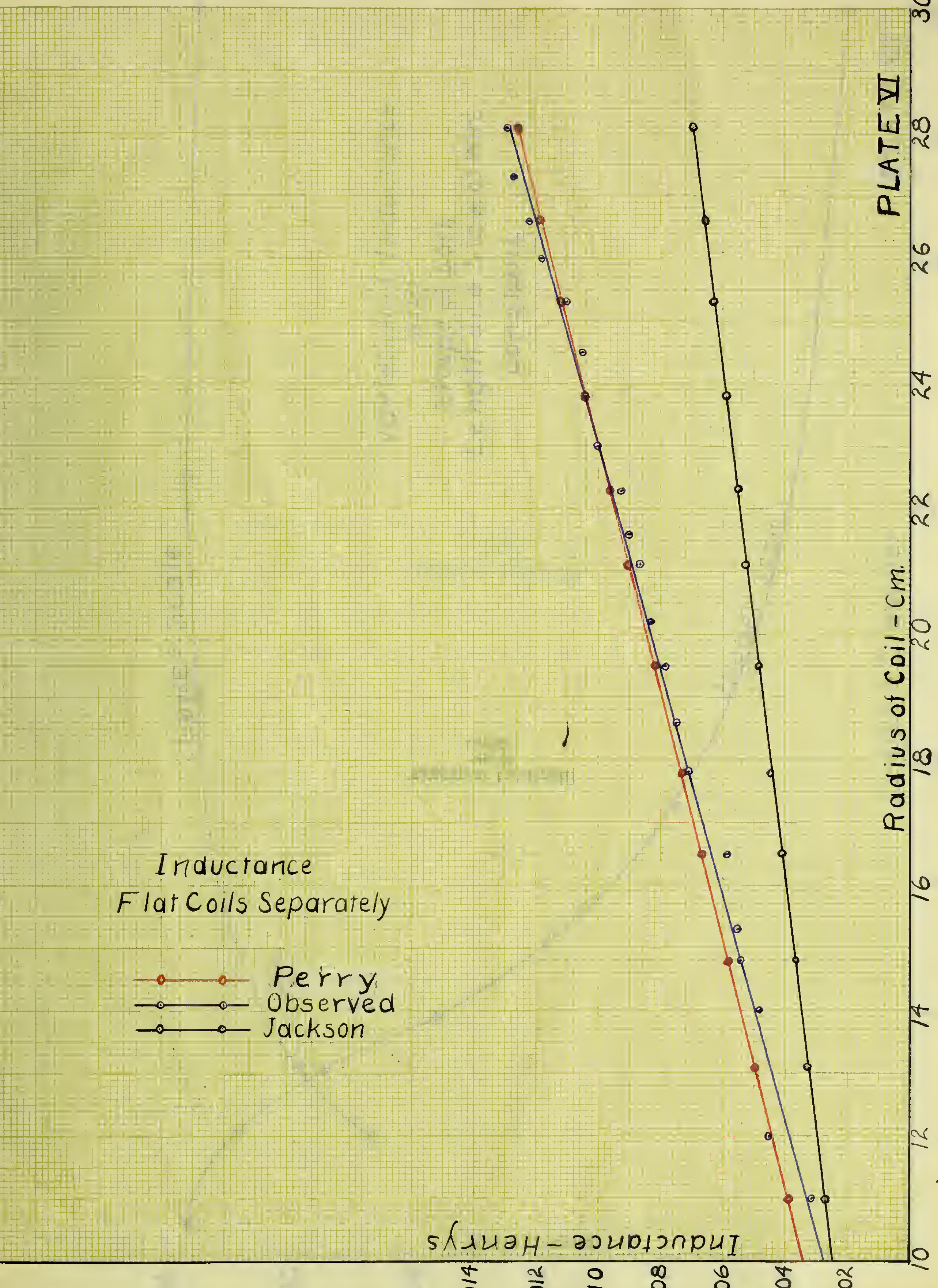
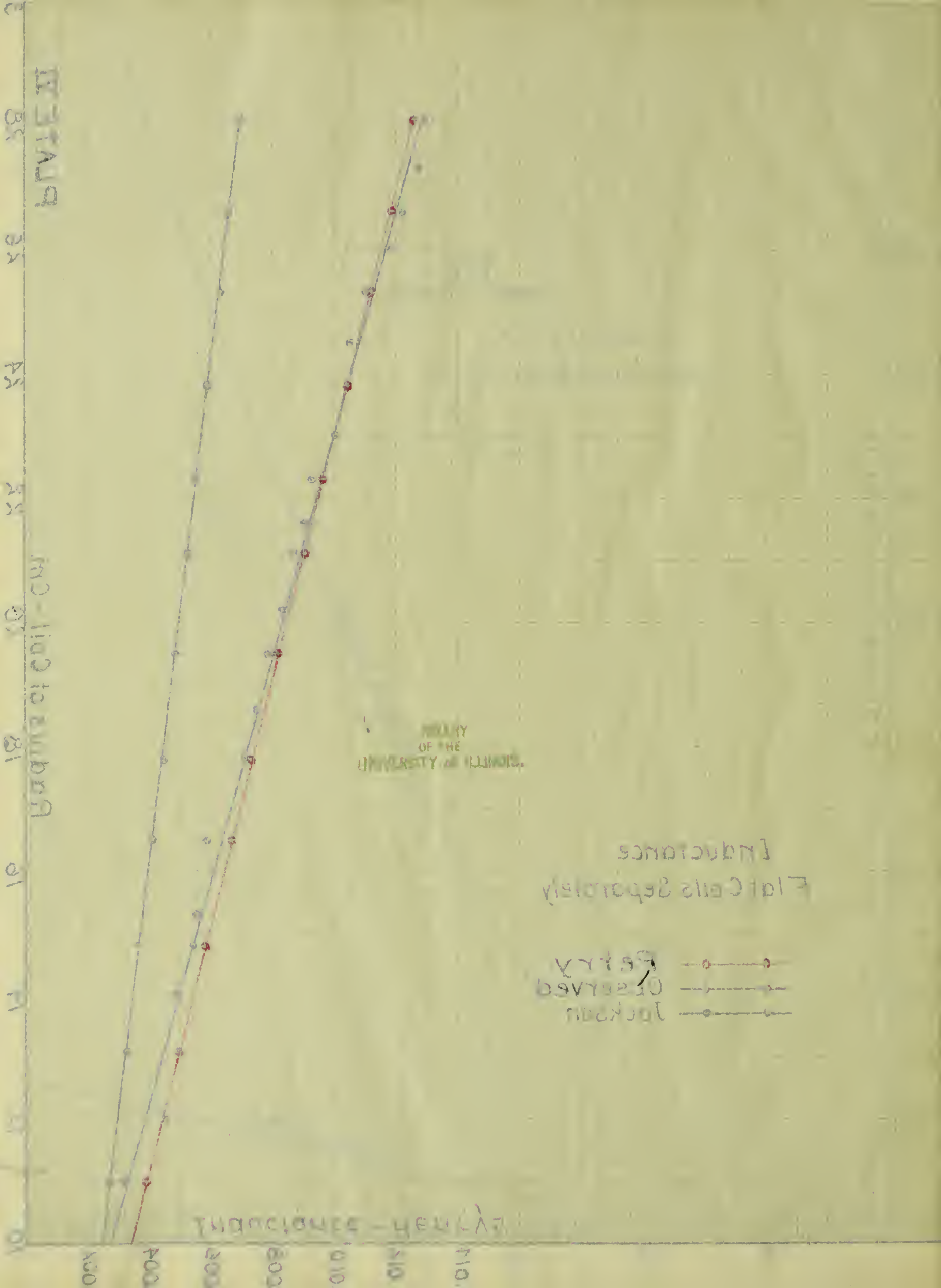

Inductance
Flat Coils Separately
Inductance - Henrys
Theoretical
Observed
Radius of Coil - Cm.
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
4
8
12
16
20
24
28

PLATE V

PLATE VII


Inductance
Flat Coils Separately
Perry
Observed
Jackson
Radius of Coil - Cm.
10
12
14
16
18
20
22
24
26
28
30
Inductance - Henrys
.002
.004
.006
.008
.010
.012
.014



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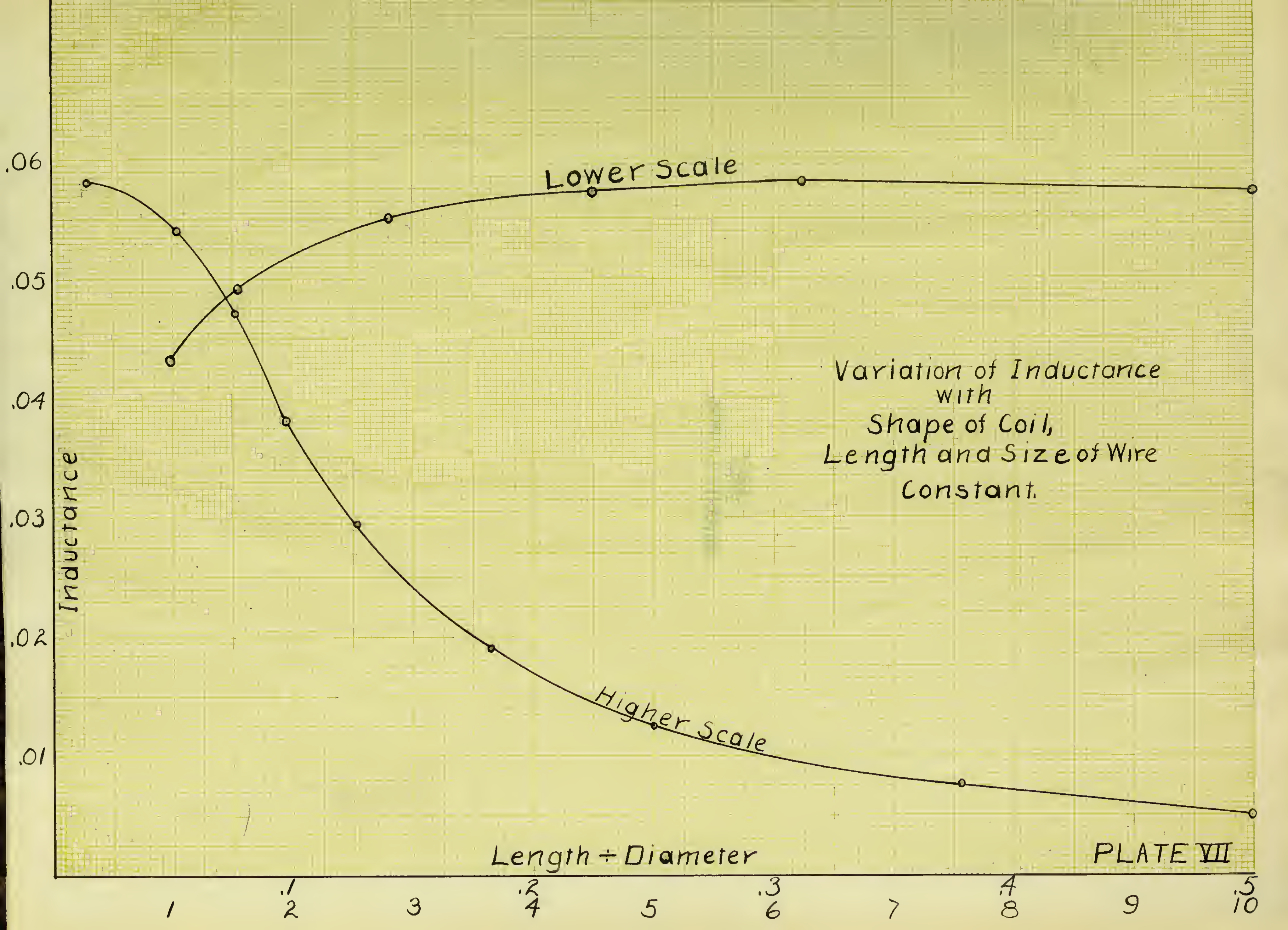
Variation of Inductance
with
Shape of Coil,
Length and Size of Wire
Constant.
Lower Scale
Higher Scale
Inductance
.06
.05
.04
.03
.02
.01
Length ÷ Diameter
.1
.2
.3
.4
.5
1
2
3
4
5
6
7
8
9
10

PLATE VII

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